Acoustic Resonance Classification of Swimbladder-Bearing Fish

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LONG-TERM GOALS

To understand and exploit the resonance scattering by swimbladder-bearing fish (typically in the 1-10 kHz frequency region). Exploitation of the resonances can significantly reduce ambiguities in interpreting acoustic scattering in terms of meaningful biological parameters compared with traditional higher frequency approaches and other lower frequency narrowband approaches.

OBJECTIVES

To conduct a new class of quantitative acoustic studies of scattering by swimbladder-bearing fish utilizing new broadband-acoustic technology that is optimized for use in the resonance scattering region of fish.

APPROACH

This research is principally focused on taking advantage of a modified commercial system that was originally designed for marine geological and gas/oil exploration. It is especially attractive for use in studying swimbladder-bearing fish because this system was optimized for use in the frequency band in which swimbladders may resonate. The off-the-shelf sensors on the system (in particular, the transmitters and receivers) were selected and configured in a manner best suited for the fish application. The system is being used for studying distributions of fish in their natural habitat. The research is part of a NOAA/NMFS fisheries study and includes trawling for sampling the fish and traditional high frequency echo sounders for comparison. Data are being interpreted in terms of physics-based scattering models whose parameters may be determined empirically as a result of the measurements. Tim Stanton oversees the entire program and is involved in every aspect. Dezhang

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14. ABSTRACT
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Chu participated in finalizing system specifications, conducting the system calibration, participating in the first at-sea study, and processing the data. Cindy Sellers participated in both at-sea studies and processing the data. Mike Jech conducts the biological sampling, performs high frequency acoustic surveys, and is involved in the design and execution of the cruises. NRL (led by Roger Gauss) participated in the second cruise in a pilot study to use their prototype mid-frequency broadband system for long-range detection and classification of fish.

WORK COMPLETED

The year focused principally on processing and analyzing data from the September 2008 cruise, calibration of data from September 2008 cruise in subsequent measurements at Seneca Lake (NRL system only), presentation of new results at conferences, publishing a conference proceedings summarizing some of the new results, and preparation of results for new manuscripts in journals. In addition, the major paper submitted in the previous year that summarized the new broadband methods we have developed and the first ocean application of the broadband system for resonance classification of swimbladder-bearing fish was accepted for publication.

1. Calibration of NRL broadband acoustic system at Seneca Lake.

One month after the September 2008 cruise, the NRL source/receiver system was calibrated for absolute source and receiver level at Seneca Lake. Part of the calibration involved measuring relative phases across the various array channels. (The WHOI broadband acoustic system and NOAA narrowband acoustic system were calibrated at sea during the Sept. 2008 cruise).

2. Data processing and analysis of September 2008 cruise.

The cruise provided an extensive set of complementary and high quality data. This was a two-ship experiment over Georges Bank, about 100 miles off Cape Cod, MA. The work focused near the NE corner of the bank near the 200 m contour. The WHOI/NRL team was on the R/V Endeavor and the NMFS team was on the FR/V Delaware-II. The Endeavor activities principally involved use of two mid-frequency acoustic systems—the WHOI-Edgetech broadband system that looked in the downward direction and the NRL broadband system that looked horizontally. The Delaware-II activities principally involved studying the distributions of fish using downward looking narrowband high frequency echosounders and using nets to sample the fish. The NRL system was deployed principally during the day and the WHOI system was deployed principally at night, collectively making up a full 24-hour day of measurements each day. Activities of both ships were coordinated via ship-to-ship communication (radio and e-mail) so that acoustic echoes measured by the WHOI and NRL systems could be related to net sampling on the Delaware-II.

A "hot spot" involving dense aggregations of fish was immediately discovered at the first station and the majority of the activities of the 10-day cruise focused on that area. Other areas within the NE region of Georges Bank were also studied with the two ships. In addition to the science phase of the cruise, the downward looking systems from each ship were calibrated at sea (the NRL system was calibrated later as described above), providing for calculating absolute levels of volume scattering strength in the data processing.

a. Processing and analyzing data from WHOI broadband system (short-range, downward-looking). Aggregations of fish were identified in the echograms (matched filtered) and the acoustic data in each aggregation were systematically processed and analyzed. Within each aggregation, 10's of data windows were formed. For each sample window, a plot was made containing the following broadband information: self-noise, raw echo value, calibration data from standard target (sphere), final calibrated fish echo data (volume scattering strength). From these diagnostic plots, the SNR across the frequency band was determined so that the quality of data from each sample window and from each aggregation could be assessed. The data were generally of very high quality as the signal-to-noise ratio was generally 10-25 dB across the band. Once the data quality was assessed, then resonance peaks were identified and characterized according to frequency, volume scattering strength, location within an aggregation, and depth of fish. Plots were made illustrating depth-dependence (or lack thereof) of resonance of swimbladder, as well as variation of volume scattering strength of each resonance feature within an aggregation.

b. Processing and analyzing data from NRL broadband system (long-range, horizontal-looking). Data from both deployment configurations were analyzed--- horizontal line receive array and vertical line receive array. The data were beamformed, matched filtered, and energy normalized. Echo statistics were studied for both single beam and combined beams. Spectra were formed as a function of range.

c. Processing and analyzing high frequency narrowband acoustic data and net samples from NOAA vessel. Calibrated plots of echograms of volume scattering strength were formed for all narrowband high frequency channels. Biological samples from the nets were organized according to size distribution per species and net tow. The data were further subdivided according to day/night and deep/shallow data.

d. Integrating all data. The mid-frequency broadband data from both WHOI and NRL systems were related to net samples for interpretation of the data. The high frequency acoustic data also provided information.

3. Research manuscripts:

a. The previously submitted major manuscript that described the newly developed broadband methods and application of the new WHOI-Edgetech system at sea was revised, resubmitted, and accepted for publication **(Stanton et al., accepted)**. This manuscript described the entire approach, including concept of the resonance classification system, choice of hardware, development of software, calibration procedures, field use, and interpreting data in terms of meaningful biological parameters (fish type, size, and numerical density).

b. A conference proceedings paper describing the results from the NRL broadband mid-frequency system was published **(Gauss et al., 2009).** This paper describes the observation of patchy echoes at distances as great as 10 km, with resonance properties consistent with those due to the swimbladder-bearing fish sampled at that site.

c. In addition to scholarship concerning new results, Stanton was invited by the Marine Acoustics Society of Japan to write a review of the past 20 years of broadband acoustic scattering research conducted by the WHOI bioacoustics group (active acoustics component). The work describes the various laboratory measurements of broadband acoustic scattering by zooplankton, fish, squid, benthic shells, and machined objects, the scattering models developed that were inspired and grounded by the measurements, signal processing associated with broadband acoustics techniques, and ocean studies to date (including this project) involving use of broadband sound to study marine organisms **(Stanton, 2009).**

d. As described in the "Related projects" section, data collected through this grant are used by Stanton and Chu in another ONR grant (Undersea Signal Processing) to study the echo statistics associated with patches of fish in the resonance scattering region (2-4 kHz). A paper describing this analysis was submitted and accepted (after revisions) for publication this year **(Stanton and Chu, accepted).**

e. Analyses for two new papers have been "roughed in" concerning the following:

i. Mixed assemblages—using the WHOI-Edgetech broadband system (downward-looking, short-range) to map the distributions of small and large fish that are each within a patch (Figs. 1, 2)

ii. Resonance classification and characterization of patchiness over large scales (10 km) using the NRL horizontal-looking long-range system (Figs. 3, 4).

RESULTS

1. *Characterization of mixed assemblages of fish (short-range, downward-looking broadband system).*

a. Through use of the broadband sound, we have been able to infer the number of major size classes present in each aggregation. For example, in aggregations of fish near the bottom, there was only one resonance (at about 3 kHz), indicating the presence of one major size class. However, in aggregations of fish in the upper water column there were commonly two resonances (at about 1.7 and 3 kHz), indicating the presence of two major size classes (Fig. 1). Net samples indicate that the near-bottom fish were approximately 25 cm in length (mostly Atlantic herring), while the fish in the upper water column were a combination of fish approximately 25 cm in length (mostly Atlantic herring) and approximately 2-5 cm in length (a mix of species).

b. Within the mixed assemblages, we have used the resonance information to map the intensities of the resonances of the two size classes of fish (Fig. 2). With this information, we have inferred that in one aggregation, fish from both size classes are approximately uniformly distributed throughout the aggregation. However, in another aggregation, the smaller size class of fish was mostly concentrated near the top (shallow) portion of the aggregation.

2. *Spatial and temporal variability of fish aggregations (long-range, horizontal-looking broadband system).*

Through use of the beamformed data, we have been able to study the spatial and temporal variability of the distributions of fish. For example, the energy-normalized matched filtered data showed significant variability in the echoes, both spatially (using a towed horizontal line receive array) and temporally (using fixed-station vertical line receive array) (Figs. 3, 4). Furthermore, the echoes showed a strong resonance of about 3 kHz at ranges as great as 10 km (Fig. 3), which is consistent with swimbladder resonances of the fish present. These data, in combination with net samples made near the measurements, illustrate the highly variable nature of the distributions of fish, both in space and time.

3. *Depth-dependence (or lack thereof) of swimbladder-resonance (short-range, downward-looking broadband system).*

We have studied the resonance frequency as a function of depth for many sample windows and from many aggregations of fish. We observed that some of the resonances (which are "tracked" from depth to depth) are depth dependent according to Boyle's law. However, other resonances are not. Specifically, the mix of small fish (2-5 cm) had resonances that were relatively independent of depth. These differences are attributed to the differences in physiology of the swimbladders of the larger fish (principally Atlantic herring) and smaller fish (mix of species other than herring).

IMPACT/APPLICATIONS

There is potential impact in several major categories:

1) The improvements of the WHOI-Edgetech (short-range downward-looking) system over the past several years have demonstrated that resonance classification with this type of system can be performed over a wide range of geometries, including towing near the surface and imaging the entire water column and towing deep near the fish.

2) The resonance classification of the mixed assemblages of fish provided a powerful and unique "view" into the aggregation. Information that is not observable with narrowband acoustic systems or through nets, the broadband system provided quantitative information on the spatial distribution of each major size class within the aggregations. Differences in spatial patterns between the large and small fish were observed in one aggregation, which can lead to better understanding of the behavior of the fish.

3) The results of the pilot experiment involving the NRL long-range horizontal-looking mid-frequency system demonstrated the promise of use of resonance classification at long ranges (at least to 10 km). In addition to providing information on the spatial and temporal variability of fish aggregations, the broadband data can be used to reduce or eliminate ambiguities that would otherwise be associated with narrowband long-range systems. For example, we observed that the resonance frequency of Atlantic herring was strongly dependent upon depth. During a diurnal migration, a lower frequency narrowband long-range system might detect the fish before the migration while they still reside near the surface (when the resonance frequency is near the frequency of the system). However, after the migration, the narrowband system might *not* detect the fish (when the resonance frequency becomes far from the narrowband frequency). This issue can be addressed through use of a broadband system that might detect both resonance frequencies, before and after migration, as a result of the wide range of frequencies the system uses.

4) The fact that the fish echo data from the long-range system "survived" the energy normalizer indicates the importance of accounting for fish in Navy classifiers (they are currently not accounted for).

5) The observed depth-dependence (and lack thereof) of the resonance frequency of the different types of swimbladders of the different species of fish can be used in refining existing acoustic scattering models for prediction of reverberation and interpretation of these data.

RELATED PROJECTS

We are being funded through the Undersea Signal Processing Division of ONR to study the statistics of the fish echoes (sequence of grants N00014-07-1-0232 and N00014-09-0428). The data from this (Biology) program are being used in two ways: 1) The statistics of the mid-frequency echoes have been studied in relation to a combination of the patchiness of the fish and acoustic beampattern. The studies show that the echoes are strongly non-Rayleigh which may need to be accounted for in ASW systems. Several probability density functions (PDF's) have been used or developed to describe the statistics. 2) The echograms from the high frequency (high resolution) channels have been used to study the statistics of the dimensions of the patches and compared with mathematical-ecology-based predictions of patch statistics. This analysis can ultimately enable prediction of echo statistics for Navy systems due to the combination of probability of occurrence of patches and probability of size of patches. Also, this analysis can ultimately lead to a better of understanding of fish behavior, as the type of behavior is linked to the patch statistics.

PUBLICATIONS

Gauss, R.C., J.M. Fialkowski, E.L. Kunz, R. Menis, T.K. Stanton, C.J. Sellers, and J.M. Jech (2009), "Clutter variability due to fish aggregations: mid-frequency measurements in the Gulf of Maine," in *Proceedings of The 3rd International Conference & Exhibition on "Underwater Acoustic Measurements: Technologies and Results*," ed. J.S. Papadakis and L. Bjorno, 21-26 June 2009, Nafplion, Peloponnese, Greece (F.O.R.T.H., Hellas, Greece), pp. 459-466.

Stanton, T.K. (2009), "Broadband acoustic sensing of the ocean," J. Marine. Acoust. Soc. Jpn. 36, 95-107.

Stanton, T.K. and D. Chu, "Non-Rayleigh echoes from resolved individuals and patches of resonant fish at 2-4 kHz," IEEE J. Ocean. Eng. [accepted, refereed]

Stanton, T.K., D. Chu, J.M. Jech, and J.D. Irish, "New broadband methods for resonance classification and high-resolution imagery of swimbladder-bearing fish using a modified commercial broadband echosounder," ICES J. Mar. Sci. [accepted, refereed]

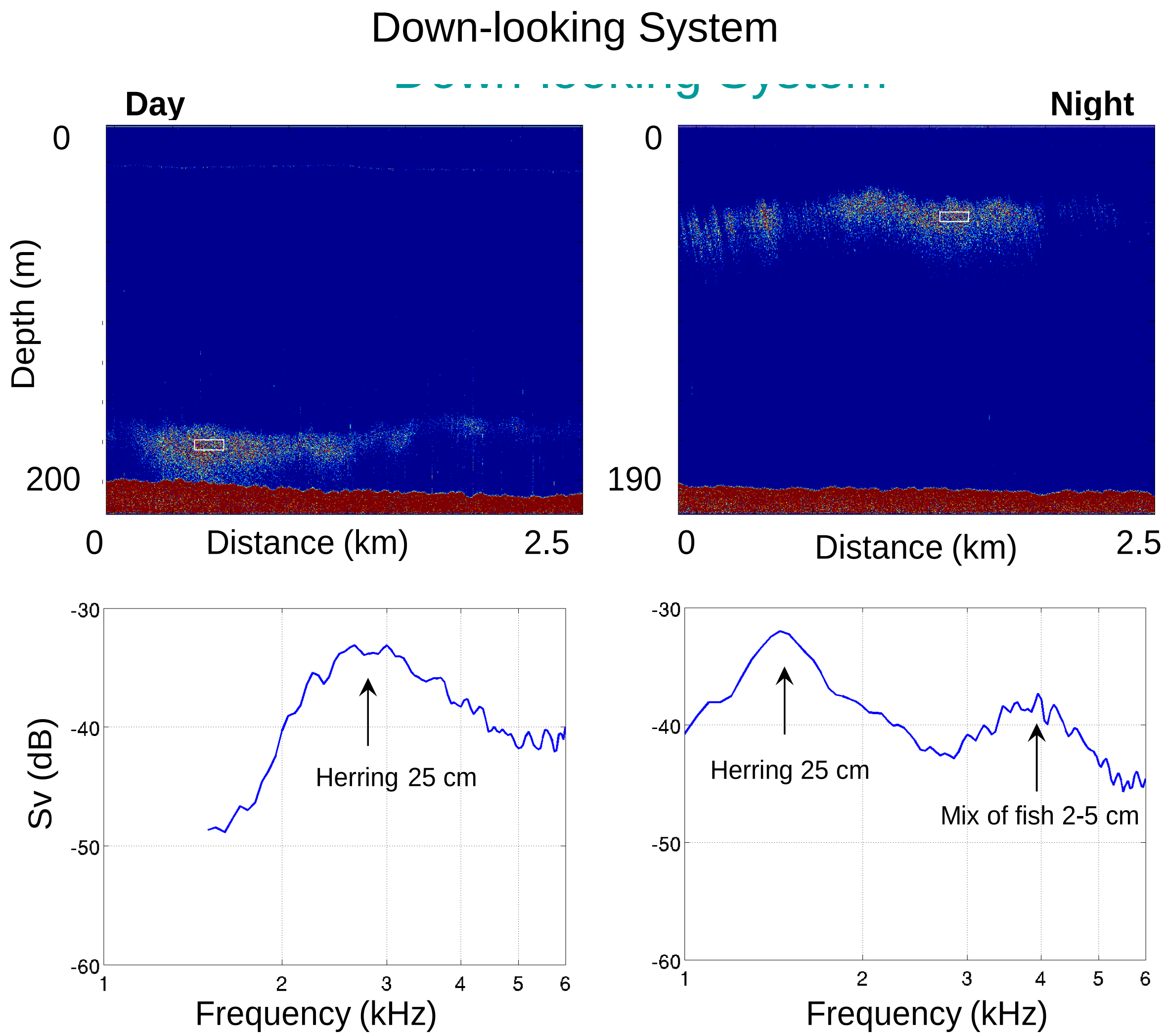

Figure 1. Mid-frequency echograms collected in the day (left) and night (right) by WHOI short-range downward-looking system in 2008. The resonance from the herring is shown to decrease once they migrate to shallow depths. Also, in the upper water column (right) the broadband data are shown to discriminate (spectrally) between small and large fish. Note that, although the system response is most sensitive at frequencies above 1.5 kHz, the scattering was so strong in the data in the right plots that the echoes were detected below 1.5 kHz as shown.

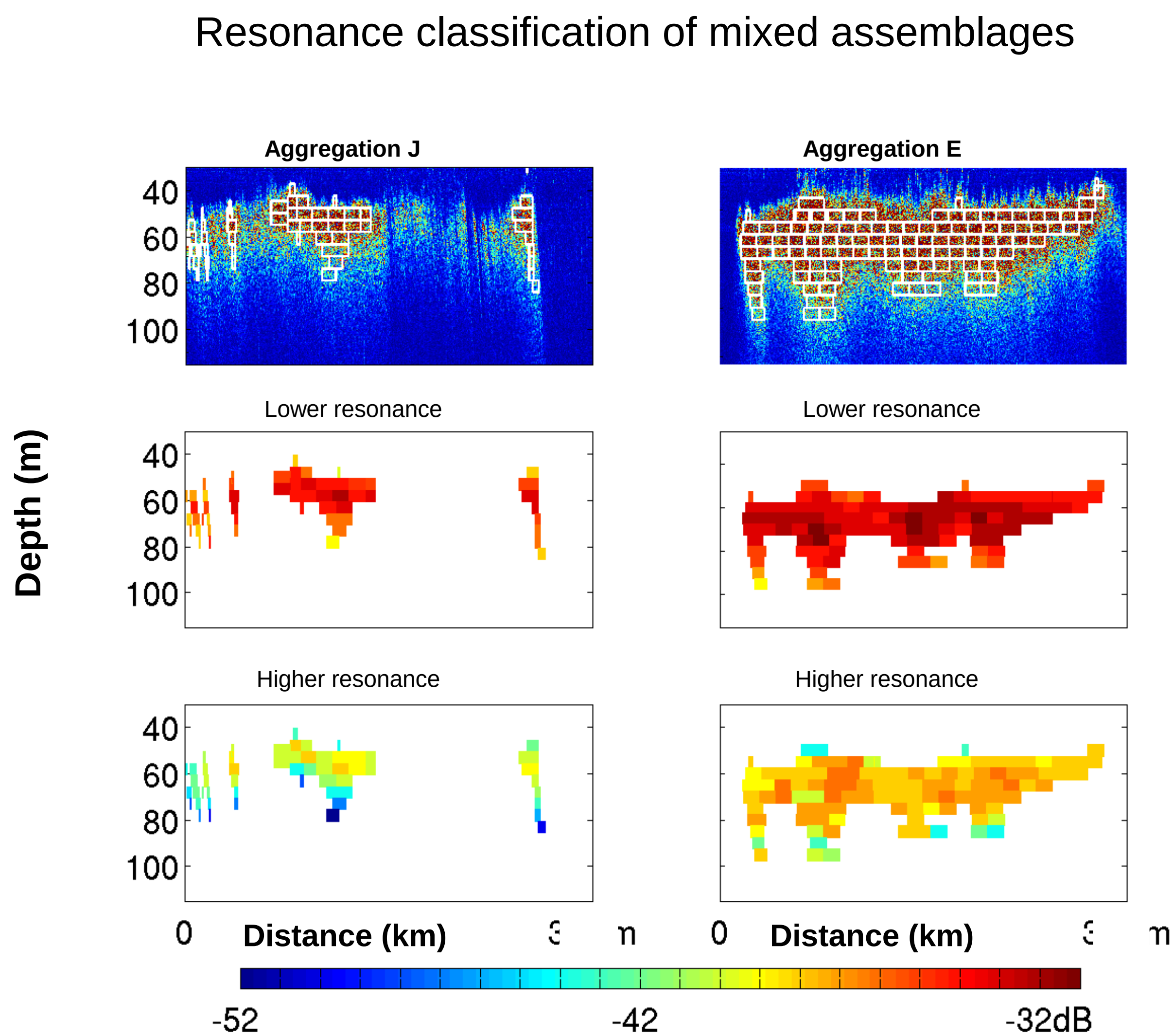

Figure 2. Mixed assemblages of fish are studied in 2008 with the WHOI short-range downward-looking mid-frequency system. Bimodal resonance data, such as shown in Fig. 1, are used to estimate as a function of depth the relative numerical density of each size class of fish (large and small) throughout each patch. In Aggregation J, the larger fish are shown to be nearly uniformly distributed throughout the patches, while the density of smaller fish decrease dramatically with depth (density at bottom of patch is less than 1/10 density at top of patch). Here, volume scattering strength is plotted in the lower four panels for each resonance. Numerical density of each size class is assumed to vary directly with volume scattering strength in this interpretation.

Long-range horizontal-looking sonar

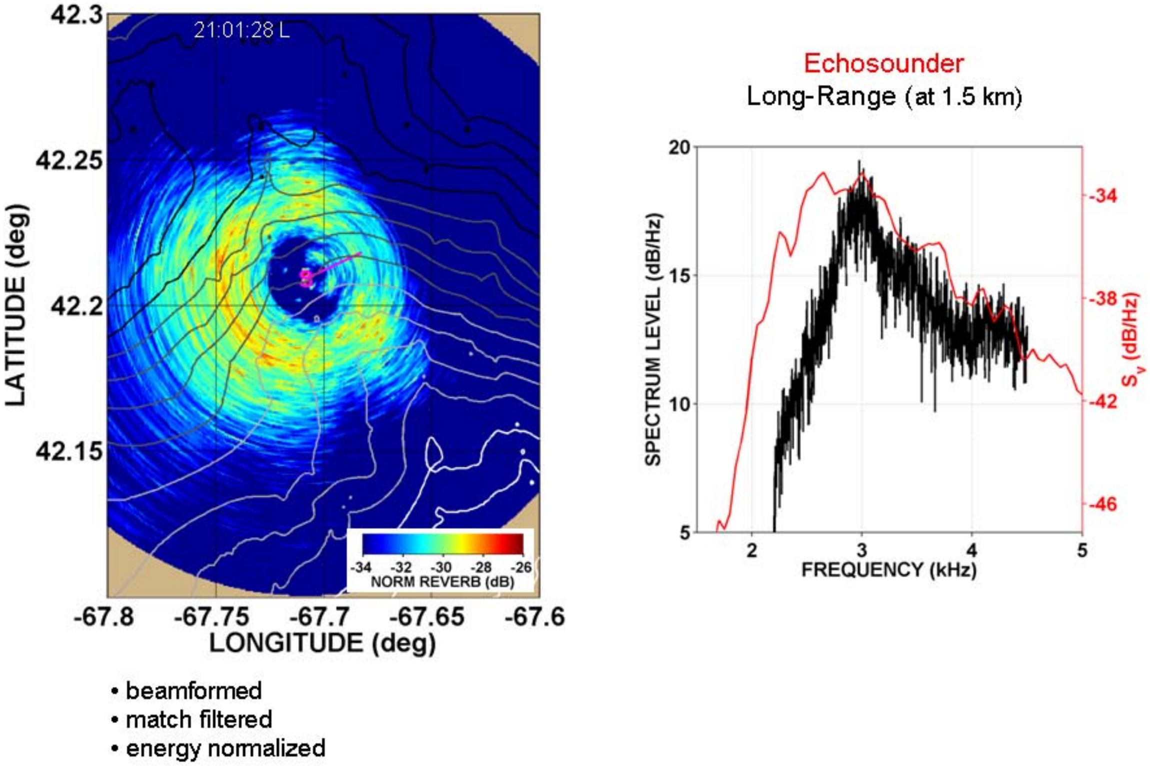

Figure 3. Long-range horizontal-looking data collected by NRL mid-frequency system in 2008. Patches of fish were observed out to 10 km and with a resonance of about 3 kHz. Data collected with towed horizontal line array.

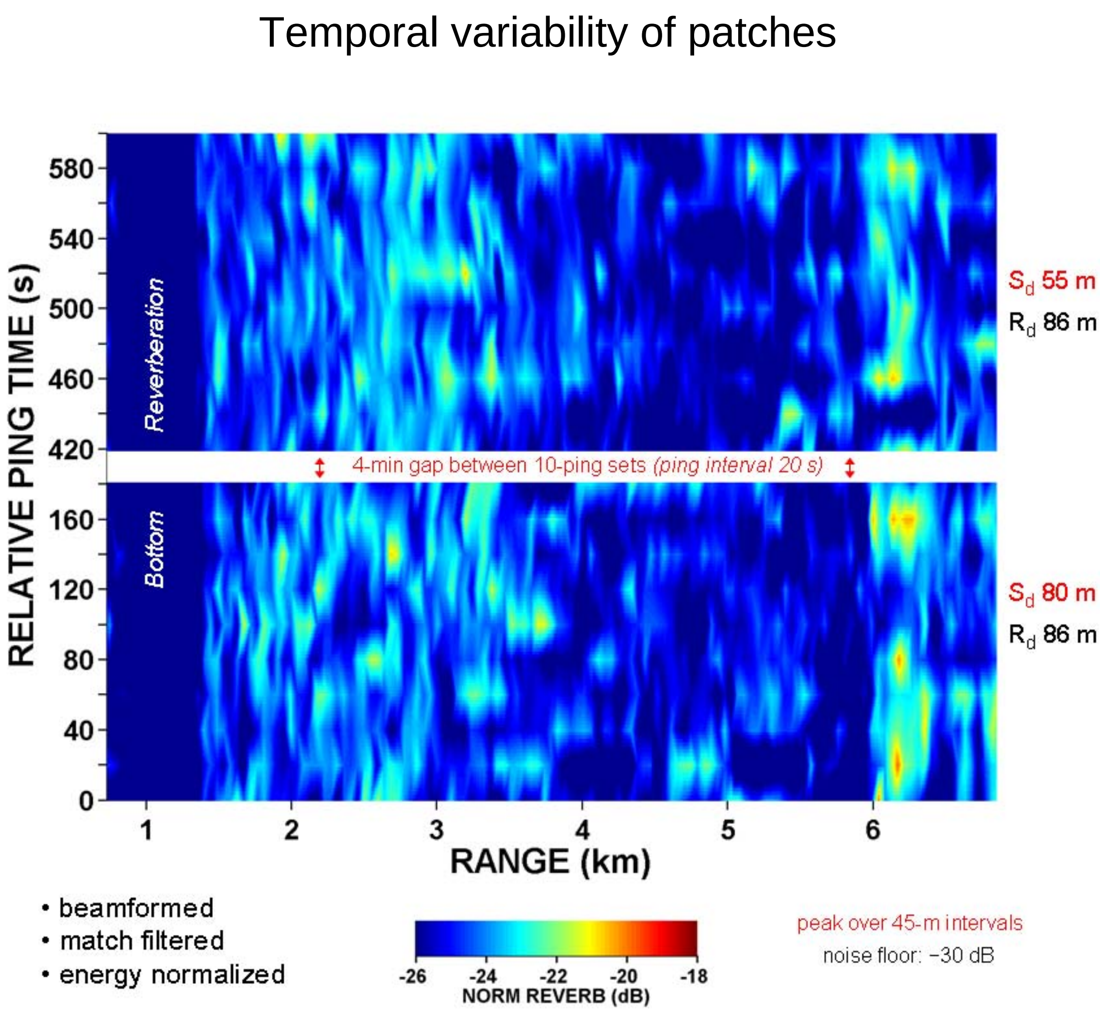

Figure 4. Time series of 20 pings from NRL long-range system while at fixed station (vertical line array configuration). A 1-sec.-long chirp signal spanning 2.5 – 3.5 kHz was used in this particular measurement. The energy normalized matched filter data show the temporal variability of patches of fish at 6 km range.